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DETERMINATION OF CRATERING ENERGY DENSITIES FOR METAL TARGETS BY MEANS OF REFLECTIVITY MEASUREMENTS

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DETERMINATION OF CRATERING ENERGY DENSITIES FOR METAL TARGETS BY MEANS OF REFLECTIVITY MEASUREMENTS

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Any attempt to estimate the lifetime of satellites or satellite components exposed to the high-speed meteoroid environment in the vicinity of the Earth requires information in two areas. First, there is required knowledge of the damage to a structure surface resulting from an encounter with a single meteoroid (if not the understanding of all the complex phenomena that occur during such an impact). Then there is required reliable information regarding the number of encounters, with meteoroids of different size, speed, and composition that can be expected to occur in a given time in orbit. Unfortunately, for the satellite lifetime estimates, information in both these areas is either unsatisfactory or lacking. The work reported herein was undertaken to determine the damage to surface optical properties due to exposure to impact with high-speed micron-size particles and thus contribute some information in the first area mentioned above.

Polished aluminum surfaces were bombarded by clouds of high-speed SiC particles having an average diameter of 6 μ. The number, size, and velocity of the particles was either known or measured, and with the total kinetic energy of the cloud characterizing the exposure, changes in reflectivity of the exposed surfaces were measured with an infrared spectrometer. A good correlation of the measured reflectivity before and after exposure was obtained with the equation[1]

$$\bar{\rho}_f = \bar{\rho}_i \left[1 - \left(1 - \frac{\bar{\rho}_\infty}{\bar{\rho}_i}\right)\left(1 - e^{-K_1 \epsilon}\right)\right] \tag{1}$$

where

$\bar{\rho}_f$ average final reflectivity of area A_0 after exposure to ϵ

$\bar{\rho}_i$ average initial reflectivity of area A_0, (0.97 for polished Al)

$\bar{\rho}_\infty$ average reflectivity after infinite exposure, (0.15 for target assumed coated with projectile material)

K_1 empirical constant, 0.229/joule falling on A_0

ϵ $\sum_{i=1}^{N} \frac{1}{2} m_i v_i^2$, total kinetic energy of particle cloud falling on area A_0, joules

In the development of this equation, it becomes clear that the constant K_1 is the percentage of fresh area damaged per unit impact energy. With the assumption that hemispherical shaped craters are formed on impact,[2] K_1 is related to E_{cr}, the cratering energy density, that is the projectile energy required per unit volume of the crater formed in the target.

Over the range of impact energies of interest here, the rate of surface damage can be assumed proportional to remaining undamaged area. Thus: -

$$\frac{dA_D}{d\epsilon} = K_1[A_0 - A_D(\epsilon)] \tag{2}$$

where

$A_D(\epsilon)$ area damaged by exposure to ϵ

A_0 area of undamaged 15/16-inch-diameter disk

The simplest procedure for relating K_1 and E_{cr} is to consider the initial condition of an undamaged surface. Then, for the first hit, $A_D(0) = 0$, and equation (2) can be written

$$\left(\frac{dA_D}{d\epsilon}\right)_{\epsilon\approx 0} = K_1 A_0 \tag{3}$$

If the crater volume is proportional to the projectile energy, the left side can also be written

$$\left(\frac{dA_D}{d\epsilon}\right)_{\epsilon\approx 0} = \frac{\left(\frac{3\pi^{1/2} m_p v_p^2}{4E_{cr}}\right)^{2/3}}{\left(\frac{1}{2} m_p v_p^2\right)} \tag{4}$$

where the numerator is the damaged area due to the first hit, and the denominator is the kinetic energy of first particle impingement, here in ergs. From equations (3) and (4)

$$K_1 = \frac{2}{A_0}\left(\frac{3\pi^{1/2}}{4E_{cr}}\right)^{2/3} \frac{1}{\left(m_p v_p^2\right)^{1/3}} \tag{5}$$

or

$$E_{cr} = \frac{3\pi^{1/2}}{\sqrt{2}\ (K_1 A_0)^{3/2} \left(m_p v_p^2\right)^{1/2}} \tag{6}$$

For our experimental condition (with v_p = 8400 ft/sec) the value for E_{cr} obtained from equation (6) is given in table I for an Al target. Table I also contains the experimental value for E_{cr} from references 3 and 4 as determined by impacting high-speed projectiles against Al targets and measuring the volume of the crater formed in the targets. It can be seen in table I that the value for E_{cr}, as determined from equation (6), compares well with the experimental values of references 3 and 4. It should be pointed out that the value for K_1 necessary for this calculation was obtained from only six reflectivity measurements. These reflectivity measurements were quite good, but further experimentation would provide a more accurate value for K_1.

In reference 5 the following equation is presented for the penetration of high-speed projectiles into semi-infinite targets:

$$\frac{p}{D} = 2.28 \left(\frac{\rho_p}{\rho_T}\right)^{2/3} \left(\frac{v_p}{C}\right)^{2/3} \tag{7}$$

where

p penetration

D diameter of particle

ρ_p projectile density

ρ_T target density

v_p particle velocity

C speed of sound in target

This equation has been extensively used to determine the number of penetrations expected to occur in satellite penetration experiments.[6] From this equation, E_{cr} is

$$E_{cr} = \left(\frac{C^2}{94.4}\right)\left(\frac{\rho_T^2}{\rho_p}\right) \tag{8}$$

Values for E_{cr} calculated from equation (8) are also presented in table I for comparison with the experimentally determined values. Notice that equation (8) underestimates considerably the cratering energy density as compared with the experiments and, hence, would overestimate penetrations expected to occur in Al. This suggests that great care must be taken when trying to determine meteoroid flux from satellite penetration experiments, and that flux estimates from these experiments may be low and are very approximate at best. The possibility of measuring micrometeoroid flux in the vicinity of the Earth with a calibrated reflectivity sensor is being considered.

TABLE I - COMPARISON OF CALCULATED AND EXPERIMENTAL VALUES OF CRATERING ENERGY DENSITY

Target	Projectile		Particle velocity, v_p	E_{cr} from eq. (8), ergs/cc	E_{cr}, from experiment, ergs/cc	Reference
	Material	Density, ρ, gr/cc				
Al-1100	SiC	3.2	8400 ft/sec	6.26×10^9	2.36×10^{10}	Eq. (6)
Al-2014	WC	15.6	$<$49,200 ft/sec	1.28×10^9	2.25×10^{10}	Ref. 3
Al-75 St	Steel	7.83	$<$49,200 ft/sec	2.56×10^9	3.90×10^{10}	Ref. 3
Al-2024-T3 and 24 St	Al	2.7	8000 ft/sec	7.42×10^9	2.49×10^{10}	Ref. 4

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